PRECISION NITROGEN FERTILIZATION: A CASE STUDY FOR DUTCH ARABLE FARMING

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ABSTRACT

Arable farming systems in the Netherlands combine high yields with high inputs of fertilizers and biocides. Management operations are highly dynamic (*e.g.*, multiple fertilizer applications in a growing season) and environmental constraints are continuously being tightened. In this setting an efficient use of inputs is crucial. Precision agriculture aims at increasing the efficiency by incorporating spatial and temporal variability into farm management operations. A methodology developed for this purpose is presented in a case study for nitrogen (N) fertilization in winter wheat (*Triticum aestivum* L.). Experiments were conducted on 16 ha field, located on a commercial arable farm in the southwestern part of the Netherlands. A forward-looking approach was pursued, enabling the farmer to respond pro-actively to a near depletion of N in (part of) the field. Simulation models and real-time weather data were used to keep track of actual soil N levels. Spatial variation was incorporated through the concept of management units: areas of land with relatively homogeneous properties in terms of water regimes and N dynamics. Early warning signals, generated once soil N concentrations dropped below a critical threshold, were used to optimize the timing of multiple split fertilizer applications. Fertilizer rates were determined through exploratory simulations, calculating the amount of mineral N required under 'normal' conditions. Results indicate that fertilizer inputs can be reduced by 15-27%, without affecting grain yields or protein content. The general concept of early warning based on dynamic simulation is applicable to a wider range of crops and farm management operations (e.g. 'precise' irrigation).

Keywords: precision agriculture, N fertilization, real-time modeling, management units.

INTRODUCTION

Nitrogen (N) emissions to groundwater and surface waters are a major concern in many regions. Given the fact that agriculture is the main source of these emissions, the European Community (EC) launched several directives to "reduce water pollution caused or induced by nitrates from agricultural sources" (EC-Council Directive, 1991). Stimulated by these directives, individual countries are in the process of implementing a series of policies to tighten environmental constraints. In the Netherlands this has resulted in an N accounting system, referred to as 'MINAS'. The system will be used to charge levies on budgetary N surpluses at the farm level and is scheduled for gradual implementation over the period 1998-2002. The final objective is to meet the 1980 EC-Drinking Water Directive in both groundwater and surface waters by limiting nitrate concentrations to 50 mg NO_3^- per liter (= 11.3 mg N l^{-1}).

It remains questionable whether a relatively simple accounting system will suffice to control N losses. Several important processes, such as the net-mineralization of N from soil organic matter (SOM), are difficult to quantify and therefore excluded from input-output budgets (so called 'farm-gate approach'). Empirical thresholds for levy-free N surpluses are fixed at preset values (e.g. 100 kg N ha^{-1} for arable land in 2008) (Oenema *et al.*, 1997), hereby neglecting the effect of soil heterogeneity.

A more flexible and mechanistic approach to fertilizer management, applying knowledge on fundamental processes and dealing with different sources of variability, could increase control over N emissions. Precision agriculture (PA) offers great potential in this respect: incorporating spatial and temporal variation will increase fertilizer use efficiency and enable farmers to stay within limits imposed by current and future policies.

A decision support system (DSS) for PA is currently being developed in the Netherlands. The system, which focuses on arable farming and reflects Dutch conditions, provides a tool-kit to optimize the timing and spatial distribution of consecutive split fertilizer applications. Basic procedures applied in this tool-kit were presented by Van Alphen and Stoorvogel (2000a), along with the results of a fertilizer experiment conducted in a winter wheat field during the 1998 growing season. The DSS proved efficient in reducing fertilizer inputs (-55 kg N ha^{-1} or -23%), while slightly increasing grain yields (+0.28 ton ha^{-1} or +3%). These results were verified in a second experiment, which was conducted a year later on a different field. Results of the second experiment are presented in this paper.

Essentially, the DSS uses a mechanistic simulation model to quantify (i) soil mineral N levels and (ii) N uptake rates on a real-time basis. Early warning signals are generated once N concentrations drop below a critical threshold level, indicating that additional fertilizer should be applied (N fertilization in winter wheat may include up to 4 consecutive applications). Spatial variation is incorporated through the concept of management units (Van Uffelen *et al.*, 1997). These units form the basis for precision management and were delineated in the experimental field by Van Alphen and Stoorvogel (2000b). Each unit is relatively homogeneous in terms of water regime and N dynamics. Simulations are conducted for selected representative soil profiles: *i.e.*, one point-simulation for each management unit.

MATERIALS AND METHODS

Study Area and Experimental Field

Research was conducted on a commercial arable farm in the central-western part of the Netherlands (51.7N, 4.0E). The farm covers an area of approximately 100 ha and applies a crop rotation of winter wheat, consumption potatoes and sugar beet. Soils originate from marine deposits and are generally calcareous with textures ranging from sandy loam to clay. They are characterized as fine, mixed, mesic Typic Fluvaquents (Soil Survey Staff, 1998) or Mn25A-Mn45A on the Dutch 1:50,000 soil map (Vos, 1984). With excellent drainage conditions, controlled by a dense system of pipe-drains, the area is considered prime agricultural land.

The fertilizer experiment was conducted on a 16 ha field seeded to winter wheat (*Triticum aestivum* L.) in November 1998. Soils were the most prominent source of variability, expressed through differences in topsoil texture (25% $\leq$ clay content $\leq$ 50%) and SOM content (0.6$\leq$ SOM content $\leq$ 5.8).

Soil Database

In the spring of 1997, a detailed 1:5,000 soil survey was conducted in the study area counting approximately six soil auger observations per hectare. Results were stored in a soil database containing soil physical and soil chemical properties for individual soil layers. Texture and SOM content were estimated directly in the field and tested against a limited number of laboratory measurements to ensure accurate characterization. Based on these properties, soil layers were grouped into relatively homogeneous classes as defined by the 'Staringreeks' (Wösten *et al.*, 1994). This classification distinguishes between topsoil and subsoil layers, which are further differentiated by textural composition and SOM content. Sixteen classes were identified and sampled in the field. Average bulk density and saturated moisture content were determined for each class using at least 4 replicate samples.

Soil hydraulic characteristics were derived through a continuous pedotransfer function (PTF) developed at the DLO-Staring Center (Wösten *et al.*, 1998). The PTF is based on soil physical measurements for 620 soil samples collected from major soil types in the Netherlands. It relates basic soil properties, such as texture, SOM content and bulk density, to a set of Van Genuchten parameters (Van Genuchten, 1980) describing the moisture retention and hydraulic conductivity curves for individual soil layers. A sensitivity analysis by Vanclooster *et al.* (1992) identified the saturated moisture content as the most sensitive parameter affecting nitrate leaching from a Typic Hapludalf (Soil Survey Staff, 1998). Considering their results, measured saturated moisture contents were used to replace the PTF estimates.

Simulation Model

Dynamic simulations of soil-water-plant interaction were conducted with the mechanistic, deterministic simulation model 'WAVE' (Water and Agrochemicals in soil and Vadose Environment) (Vanclooster *et al.*, 1994). WAVE integrates four existing models describing: (i) one-dimensional soil water flow (SWATRER) (Dierckx *et al.*, 1986), (ii) heat and solute transport (LEACHN) (Hutson & Wagenet, 1992), (iii) N cycling (SOILN) (Bergström *et al.*, 1991) and (iv) crop growth (SUCROS) (Spitters *et al.*, 1988). Differential equations governing water movement and solute transport are solved with a finite difference calculation scheme. For this purpose soil profiles were divided into 1-cm compartments. Water movement is described by the Richards' equation (Richard, 1931), combining the mass balance and Darcian flow equations. Verhagen (1997) made two conceptual changes to the original model:

1. Water uptake by plant roots was originally modeled assuming preferential uptake in upper soil compartments, therefore excluding roots in the deeper layers. After revision, water uptake is calculated as an integral over the entire root zone.
2. Nitrogen uptake is controlled by N concentrations in the leaves. Originally, this concentration had to be specified as model input. After revision, N concentrations are calculated as a function of biomass production following an empirical relation described by Greenwood *et al.* (1990):

$$N_c = 5.7 \times W^{-0.5}$$

in which N_c is the critical N concentration in the leaves [%] and W is the total weight of accumulated biomass [tons of dry matter ha^{-1}].

Stress resulting from N deficiency occurs when critical N concentrations in the leaves cannot be sustained by N uptake rates. In this case crop production is reduced proportionally to the ratio of actual over required N concentrations. Water stress is calculated according to Feddes *et al.* (1978). Maximum water uptake is defined by a sink term [d^{-1}], which is considered constant with depth. Water uptake is reduced at high- and low-pressure head values according to crop-specific thresholds.

Characterizing Soil Variability: Management Units

Soil variability in the experimental field was described through the concept of management units (Van Uffelen *et al.*, 1997). These units form the basis for precision management and were delineated following procedures developed by Van Alphen and Stoorvogel (2000b).

The applied methodology characterizes soils in terms of 'functional' properties describing their water regime and nutrient dynamics. These properties are derived through multiple simulations for individual soil profiles (point simulations). With respect to the experimental field, basic soil data were available for 90 profiles sampled during the 1997 soil survey. Recorded data included hydraulic characteristics, SOM content and bulk density. Based on this information, two series of simulations were conducted describing soil behavior under the extreme conditions of a dry year (1989) or a wet year (1987). Winter wheat was chosen as the reference for crop growth simulation, using model parameters provided by Spitters *et al.* (1988) and Boon-Prins *et al.* (1993). Management parameters, specifying the timing and amount of mineral fertilizer applications, were defined according to general practice (240 kg N ha^{-1} distributed over 4 split applications). Four functional properties were considered:

1. Water stress in a dry year;
2. N stress in a wet year;
3. N leaching from root zone in a wet year;
4. Residual N content at harvest in a wet year.

The first two properties reflect the sensitivity of a soil to the effects of major growth-limiting factors. Their direct relation to crop production makes them relevant from an economical perspective. Properties three and four were included as environmental parameters, describing the pace at which nitrates are leached from the root zone.

Based on functional similarity, soil profiles were grouped into functional classes using a multivariate fuzzy c-means classifier. Three classes were identified, following from an objective data set analysis using so-called 'validity measures' (Roubens, 1982). These measures indicate the number of classes that best reflects a balance between structure and continuity (or fuzziness) that is generally pursued (McBratney and Moore, 1985). The appropriate number of classes is thus derived from the data set, thereby eliminating an important source of subjectivity from the classification.

Ordinary kriging (Journel and Huybregts, 1978) and a boundary detection algorithm were subsequently used to interpolate class information (point data) and delineate functional units in the experimental field. Four units were identified (A-D in Fig.1), each representing a spatial grouping of soil profiles with similar functional properties (*i.e.*, belonging to the same functional class). Profiles best matching the average functional properties of their class were selected as representative soil profiles. Average properties and coefficients of determination achieved through spatial grouping are presented in Table 1. Together, functional units explained >70% of the spatial variation, making them suitable entities to be used as management units for PA.

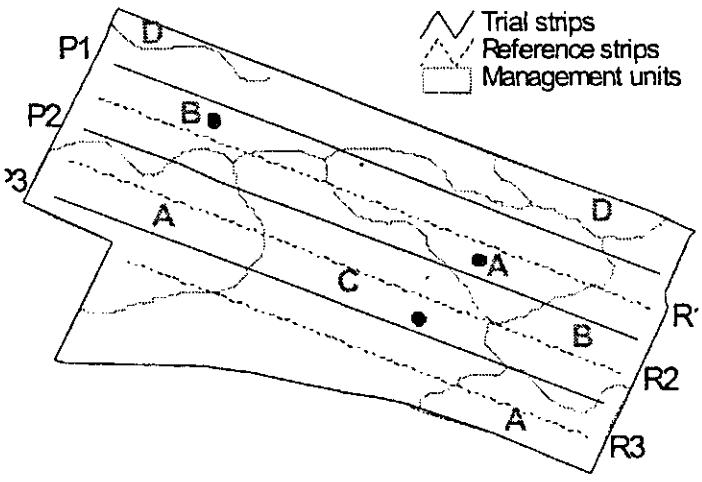

Fig.1. Experimental field with management units (A-D), representative soil profiles (•), trial strips (P1-P3) and reference strips (R1-R3).

Table 1. Average soil functional properties (± SD) of the functional classes in the experimental field; R^2 indicates the percentage of spatial variation explained by the functional units.

Class	Count[1]	Water stress[2]	N stress[3]	N leaching	N residual
				—— kg N ha^{-1}	——
1	25	0.99 (0.02)	1.00 (0.00)	29.4 (4.0)	90.1 (4.0)
2	16	0.71 (0.07)	1.00 (0.00)	37.1 (6.6)	106.3 (18.7)
3	30	0.98 (0.04)	1.00 (0.00)	36.8 (3.2)	86.9 (10.7)
4	10	0.96 (0.06)	1.00 (0.00)	56.3 (8.6)	154.5 (15.7)
R^2(%)		86	100	71	70

[1] Count indicates the number of soil profiles grouped in each class.
[2] Water stress is expressed as the ratio of actual over potential evapotranspiration (unit value indicating the absence of stress).
[3] N stress, reflecting the ratio of actual over required N percentages in the leaves, never occurred under the selected management settings and was therefore not a discriminating factor.

Experimental Setup and Field Sampling

Six strips were identified in the experimental field, all situated along tracks used by farm machinery (Fig.1). Strips P1-P3 were selected as trial strips receiving precision management. Strips R1-R3 were used as reference strips receiving traditional management. Each strip was 32m wide, corresponding to the working width of the fertilizer spreader (16m to each side). Trial strips were further sub-divided by management units A-C (unit D was outside the trial strips), among which fertilizer rates were varied.

Soil mineral N concentrations were measured in trial strips at monthly intervals. Separate samples were collected for each management unit, differentiating between 0-30cm and 30-60cm depths. Nitrate N, ammonia N and total N concentrations were measured in a 50 ml KCl (1 *M*) soil extract using the Technicon-Auto-Analyzer II. Samples collected in March were used to initialize the simulation model. Groundwater levels were measured weekly at three sites corresponding to the locations of selected representative soil profiles.

Real-time Simulations to Optimize Fertilizer Application

Nitrogen fertilization in the experimental field was optimized using the DSS toolkit developed by Van Alphen and Stoorvogel (2000a). Fertilizer recommendations were based on real-time simulations, conducted for representative soil profiles in management units A-C. Simulations quantified (i) soil mineral N levels and (ii) N uptake rates on a weekly basis. Upper-boundary conditions for the model were specified in accordance with daily meteorological records from an on-farm weather station. Soil hydraulic parameters and groundwater levels were extracted directly from the soil database.

Nitrogen levels and uptake rates were integrated over 0-90cm, corresponding to the average rooting depth of winter wheat (Boon-Prins *et al.*, 1993). Nitrogen budgets were calculated as the net-resultant of input (fertilizer application, mineralization from SOM) and output fluxes (crop-uptake, denitrification and leaching). The effects of immobilization and atmospheric deposition were assumed to be negligible over the period of the field experiment (March to July). Decomposition rates (d^{-1}) for SOM pools were taken from Droogers and Bouma (1997), who conducted incubation experiments for similar soil types in the region.

The threshold level indicating N depletion was defined at twice the uptake rate over the past week. A safety margin was thus introduced to (i) accommodate for model inaccuracies and (ii) provide a time-span for action in case weather conditions would hinder machinery from entering the field. Early warning signals were generated once soil mineral N levels dropped below the threshold in either of the management units. In reaction, all management units received additional fertilizer, using differences among N levels to vary the dosage if appropriate.

Fertilizer rates were determined through exploratory or 'forward-looking' simulations. These simulations extended upon real-time simulations using historical weather data from an 'average' year (1994). They were conducted for time intervals between consecutive applications, starting at the point where an early warning signal was generated. The length of each interval was estimated using a tentative fertilization schedule, defining the number of applications and their approximate time line. Given the interval, the required amount of mineral fertilizer was calculated and subsequently applied.

Yield Measurements

The effects of precision management were evaluated through yield measurements. Separate measurements were conducted for each experimental strip, including total grain weight, average grain moisture content and average grain protein content. After correcting for moisture variations, grain yields were calculated by dividing total grain weights (standardized at 16% moisture content) by their strip-specific surface area.

RESULTS

Model Validation

Modeling performance was tested against measurements available in the soil database. Figure 2 presents measured and simulated soil moisture contents. Measurements were collected at three monitoring sites installed in the study area during the 1997 growing season. The overall coefficient of determination is 63%. Figure 3 presents measured and simulated soil mineral N concentrations. Measurements were collected during 1998 in a 10ha winter wheat field with low soil variability. Monthly samples were taken from 9 sites and at two depths (0-30cm and 30-60cm). Including samples collected two weeks after harvest (day 229) the overall coefficient of determination equals 84%.

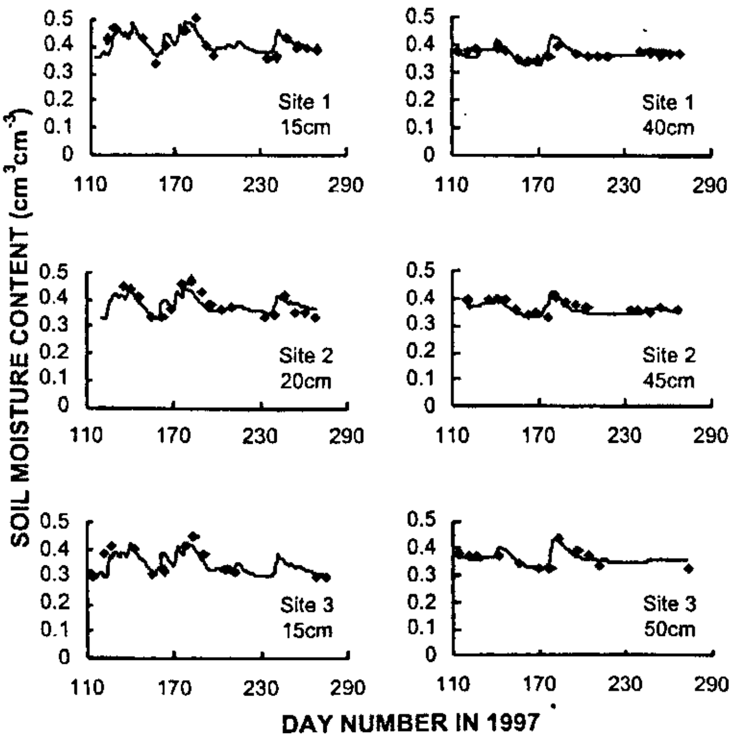

Fig.2. Measured (♦) and simulated (—) soil moisture contents (three sites, two depths).

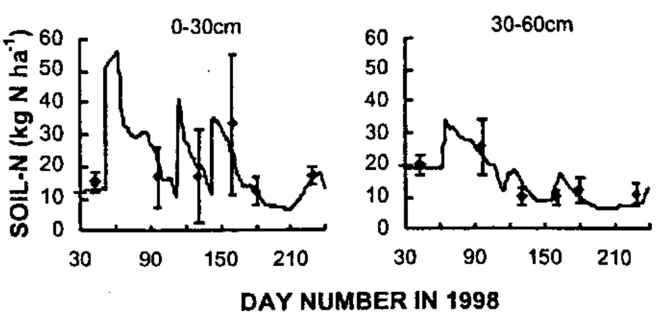

Fig.3. Measured (♦; ± SD) and simulated (—) soil mineral N concentrations. Measurements represent average concentrations derived from 9 sampling sites.

Traditional Fertilizer Application

Reference strips received uniform management according to fertilizer recommendations provided by the Dutch extension service (DLV). The basis for these recommendations was established some 20 years ago through extensive field experiments. Induced by the introduction of more productive varieties, fertilizer rates have been increasing over recent years. Nowadays, fertilizer recommendations are aimed at production levels of 12 tons ha^{-1}, assuming 25 kg of mineral N is required for each ton of wheat. Recommendations for individual fields incorporate average soil mineral N levels measured in the root zone at the start of the growing season. In the experimental field this amounted to 57 kg N ha^{-1} in 0-100cm on March 18th. The corresponding fertilizer recommendation (F_r in kg N ha^{-1}) was calculated as:

$$F_r = 300 - N_{min}$$

in which N_{min} is the average soil mineral N level measured in spring [kg N ha^{-1} in 0-100cm]. This recommendation includes a top-dressing of 40 kg N ha^{-1} to be applied just before flowering. The total recommended fertilizer rate was established at 300 - 57 = 243 kg N ha^{-1}.

Mineral fertilizer was applied using a split fertilization strategy, which has become common practice in the Netherlands. Four applications were scheduled: a base-application in March (as soon as farm machinery could enter the field), two applications during April and May (using development stage and coloring as 'triggers') and a top-dressing before flowering in June. Fertilizer rates were set at 80 kg N ha^{-1} for the base-application, 60 kg N ha^{-1} for applications 2 and 3 and 40 kg N ha^{-1} for the top dressing.

The start of the 1999 growing season was characterized by extreme rainfall. Local depressions were flooded for days in a row, causing severe damage to the crop. Once the damage proved irreversible, flooded areas were excluded from the fertilizer trial. Weather conditions started to improve by the end of January. Soils dried quickly during February, allowing the base-fertilization to be applied according to schedule (March 18th). Favorable conditions continued throughout the remainder of growing season, resulting in rapid crop development. Half way through April, crop color turned slightly paler, triggering a second fertilizer application on April 19th. A consecutive third application was performed within a month (May 14th), again triggered by slight color alteration. The final top-dressing was applied on June 1st, only a few days before flowering was witnessed (June 6th).

'Precise' Fertilizer Application

Trial strips received precision management, using model-generated early warning signals to optimize fertilizer timing. In line with the reference strips, a uniform base-fertilization of 80 kg N ha^{-1} was applied on March 18th (day 77). From this point onwards, supply and demand for N were analyzed on a weekly basis. To account for spatial variability, separate simulations were conducted for each management unit. Figure 4 presents simulated soil mineral N levels and weekly N uptake rates for the 'critical' unit (A). This unit showed the most rapid decline of N concentrations and, as a consequence, triggered the early warning signals for N depletion.

The threshold level for N depletion was first reached on April 25th (day 115). Soil N concentrations in unit A had dropped to 26 kg N ha^{-1}, while crop uptake had reached 23 kg N ha^{-1}. Within two days a second fertilizer application

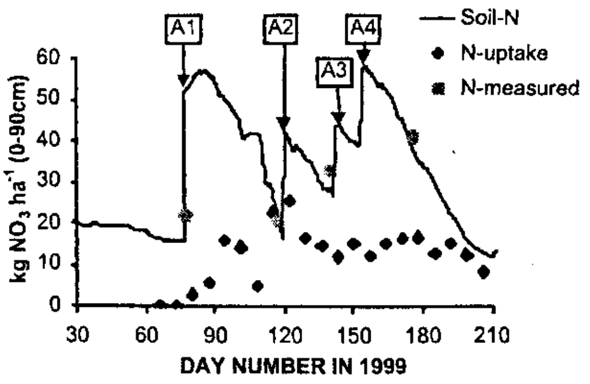

Fig.4. Simulated soil mineral N concentrations and weekly N uptake rates in the 'critical' management unit (A). Fertilizer applications on days 77, 117, 140 and 154 are indicated with 'A1' to 'A4'.

was performed (April 27th); *i.e.*, eight days after the second traditional fertilization.

The fertilizer rate for the 'critical' unit (A) was established at 55 kg N ha^{-1}. This quantity was derived through an exploratory or 'forward-looking' simulation. Starting with the situation on April 25th, the simulation covered a period of four weeks, corresponding to the estimated time interval between applications two and three (the latter was scheduled for the second half of May). Fertilizer rates for management units B and C were corrected for larger soil N concentrations present on April 25th. As the difference between units A and C was minimal (1 kg N ha^{-1}), the fertilizer rate was only adjusted for unit B (45 kg N ha^{-1} with 36 kg N ha^{-1} in the soil on April 25th).

The calculated fertilizer rate proved accurate, as threshold levels were reached for the second time on May 16th (day 136). By then soil N concentrations had dropped to 29 kg N ha^{-1} and crop uptake had reached 15 kg N ha^{-1}. A third application was performed soon after on May 21st (day 140); *i.e.*, a week later than under traditional management. The time interval to the fourth application was estimated at three weeks (flowering was expected in the first week of June). A second exploratory simulation was conducted, resulting in a recommended fertilizer rate of 35 kg N ha^{-1} for management unit A. Again the fertilizer rate was only adjusted for unit B (25 kg N ha^{-1} with 36 kg N ha^{-1} in the soil on May 16th).

The fourth and final application was not triggered by an early warning signal, but applied just before flowering (June 3rd; day 154). This is traditionally practiced to provide the crop with abundant N when grain filling starts. However, instead of applying the traditional 40 kg N ha^{-1}, fertilizer rates were calculated through a third exploratory simulation. Starting with the situation on June 3rd, the amounts of N fertilizer required for maximum production under 'average' conditions were 35 (unit A), 25 (unit B) and 30 (unit C) kg N ha^{-1}.

Fertilizer rates applied in trial and reference strips are summarized in Table 2. Precision management resulted in variable fertilizer rates ranging from 175 kg N ha^{-1} (unit B) to 205 kg N ha^{-1} (unit A). This meant a reduction of 35 - 65 kg N ha^{-1}

or 15% - 27% compared to traditional management. As a consequence, the average residual N concentration measured after harvest (August 20th) was clearly lower in trial strips (34 kg N ha^{-1}) than in reference strips (59 kg N ha^{-1}).

Table 2. Fertilizer rates applied in the experimental strips.

Date	Trial strips			Reference strips
	m.u. A	m.u. B	m.u. C	
		kg N ha^{-1}		kg N ha^{-1}
March 18th	80	80	80	80
April 19th				60
April 27th	55	45	55	
May 14th				60
May 21st	35	25	35	
June 1st				40
June 3rd	35	25	30	
Total	205	175	200	240

Table 3. Grain yields and protein contents measured in experimental strips.

Strip	Yield	Protein content
	tons ha^{-1}	%
Trial strips		
P1	11.3	13.3
P2	10.3	13.5
P3	10.5	13.3
Average	10.7	13.4
Reference strips		
R1	11.4	12.9
R2	10.9	13.1
R3	10.2	13.8
Average	10.7	13.4

Measured Grain Yields

Grain yields measured in trial and reference strips are presented in Table 3. Despite wet conditions at the start of the growing season, yield levels were relatively high. No differences were witnessed between precision and traditional management: average grain yield and protein content were equal in trial and reference strips. Precision management, however, combined these results with a significant reduction on fertilizer input.

DISCUSSION

By combining real-time mechanistic simulations with the concept of management units, an opportunity is created to optimize N fertilization in both temporal and spatial dimensions. Fertilizer management becomes more flexible and more accurate: applications no longer rely on recommended rates based on expected maximum production levels (potential yields), but are defined in accordance with specific conditions prevailing during the growing season. Nitrogen applications are triggered by early warning signals for N depletion and fertilizer rates are determined through exploratory or 'forward-looking' simulations. Excessive fertilization is thus avoided and nitrate emissions are reduced to a minimum. In addition, management becomes pro-active rather than reactive: N deficiencies are alleviated before crop condition is affected.

During the experiment, precision management proved efficient in reducing fertilizer input (15-27% reduction) without affecting grain yield and protein content. This was in line with the results of a previous experiment, when fertilizer input had been successfully reduced by 23% (Van Alphen and Stoorvogel, 2000a). Together these experiments provide strong evidence that traditional fertilizer recommendations in the Netherlands are (still) too high and that precision management can play a key role in increasing fertilizer use efficiency.

Besides quantities applied, the timing of consecutive fertilizer applications proved a discriminating factor. 'Precise' applications were performed approximately one week later than their traditional counterparts (except for the base fertilization and top dressing). This implies that early warning signals for N depletion were generated beyond the point where crop color turned paler. As yield levels were not affected, it may be concluded that slight alteration of crop color does not automatically mean that the crop is N deficient.

Fertilizer rates applied under precision management varied between 175 and 205 kg N ha^{-1}. Simulations indicated that these differences were mainly caused by mineralization of organic N. Management unit B, containing 1.8% SOM (averaged over 0-100cm), consistently received lowest rates. Units A and C, containing 0.9% and 1.2% SOM, received equal rates for applications 1-3. The fourth and final application was however lower in unit C. Together, these results illustrate the relevance of dealing with spatial variability of SOM contents.

Verhagen and Bouma (1997) showed that N leaching during winter is linearly related to residual soil N concentrations measured after harvest. Since N residues were lower under precision management (34 kg N ha^{-1} versus 59 kg N ha^{-1}), it may be concluded that N leaching was clearly reduced. This is especially relevant since reduced leaching is a priority issue for both policy makers and farmers. Quantifying this effect for the experiment would have required further analysis of the leaching potential within each management unit. This falls outside the scope of this research.

CONCLUSIONS

1. Precision management proved efficient in reducing fertilizer input (15-27% reduction) without affecting grain yield and protein content. This illustrates the key role that precision agriculture can play in increasing fertilizer use efficiency.
2. When focussing on farming systems applying a split fertilization strategy, timing should be considered equally important as spatial precision.
3. Real-time simulation of water regimes and N dynamics provides a valuable tool in optimizing fertilizer management.

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